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EXPLORATORY
ENERGY CONVERSION STUDY
of
PHOTON THERMIONICS

Quarterly Technical Progress Report No. 3

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GENERAL ⬤ ELECTRIC

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INTRODUCTION

Air Force Contract AF 33(657)-9202 was initiated to determine the feasibility of enhancing the performance of the cesium vapor thermionic converter by photon processes. The approach on this program, mainly experimental, has been to irradiate a specifically designed converter with various radiation sources.

EXPERIMENTAL CONVERTERS

During this report period, two experimental converters, a tantalum-emitter tube and a tungsten-emitter tube were constructed in accordance with the design shown in Figure 1. The distinctive feature of these tubes is the integral sapphire window and collector which permit the introduction of various radiations with a minimum of absorption. The collector consists of 0.010-inch tungsten wires embedded in grooves in the inner sapphire window. A photograph of the tungsten-wire anode seen through the sapphire windows is shown in Figure 2; the emitter surface is also visible through the windows. The emitter-collector spacing can be adjusted by means of a bellows and a micrometer fixture. The cesium reservoir is a glass appendage which is heated by a controllable oven. The temperatures of the converter proper are maintained by heating tapes.

Experiments were initiated on the tantalum-emitter converter first. Several difficulties occurred with this tube. For example, during outgassing of the emitter, a deposit formed on the center of the sapphire window. It is believed that this deposit might be caused by the interaction of the tantalum surface with the sapphire window by means of a vapor transport process, probably involving atomic hydrogen. Next, the tension in the grid wires was not sufficient to prevent sagging when the emitter was at higher temperatures because this particular grid required a second braze in its fabrication. Since the mandrel was disconnected after the first braze, it appears that the original high-temperature Th-Ti braze did not hold the tension while the second braze (copper) was made.

The third difficulty encountered with the tantalum converter was the failure of an oxide-free seal which joined the cesium reservoir to the converter proper. It is believed that a portion of this seal was not

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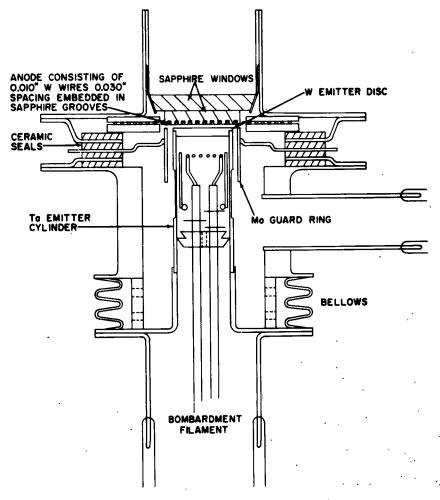
Figure 1 - Experimental Converter Designed to Test
Photon Enhancement Concept

Figure 2 - Tungsten-Wire Anode Seen Through Sapphire Window

oxide free, and that the cesium attack on this oxide caused the seal fracture. Since the converter was operating when the fracture occurred, this failure resulted in the destruction of the converter.

None of these problems arose with the tungsten-emitter tube. As experiments proceeded on this tube, however, a deposit formed gradually on the center of sapphire window (similar to the tantalum-emitter deposit); especially at the higher emitter temperatures. It is estimated that, at the completion of the experiments, the total window transmission, including corrections for the film deposit and reflection at each surface over the area of the emitter, was down to 26 percent.

RADIATION SOURCES

The two types of radiation which are considered likely to produce some effects in the converter are the cesium resonance lines (especially the 8521Å and 8943Å lines) and the ultra-violet radiation whose wavelengths are shorter than 3185Å (the wavelength corresponding to the ionization potential of cesium). The chief radiation sources are shown in Table I. A big difference between the electrical power input and the

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Table I - Radiation Sources

Lamp	Power Input (watts)	Light Input Incident on the Windows (watts/cm^2)	Characteristics
CsI-A	144	0.04 at 8943 and 8521 Angstroms	Sharp unreversed resonance lines
CsI-Hg	250	0.4 at 8943 and 8591 Angstroms	Broad reversed resonance lines
Hg lamp	58	0.07 at 2537 Angstroms	One-fifth of light output in the region of the 2537Å line.
Xe arc lamp	488	0.3 in the ultra-violet 0.3 at 8943 and 8521 Angstroms	Continuous spectrum with broad xenon lines (one of which is at 8952Å). The lamp geometry is such that radiation can be focused into the converter.
Xe flash lamp	200 watt-sec. (approx. 200,000 watts)	5 at 8943 and 8521 Angstroms 6 in the near ultra-violet	Continuous spectrum with same broad xenon lines (one of which is at 8952Å). Middle and far ultra-violet cutoff by the glass envelope.

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light input incident on the sapphire windows, as shown in this table, be-
cause the lamps used are extended sources, and the collecting area of
the windows represents a small fraction of the total solid angle into which
the lamp is radiating. For example, using the ultra-violet mercury
lamp (shown in Figure 3), even though one-fifth of the light output is in
the desired U-V (2537Å) and the converter window is opposite the re-entry
discharge column, still only about 10^{-3} of the power input is incident on
the windows. Also even though the desired radiations (i.e., the cesium
8521Å and 8943Å lines and the mercury 2537Å line) are the strongest
lines, there are many other lines and continuous regions in which energy
is dissipated. In the case of the CsI lamps and the xenon arc lamp, much
of the input energy is radiated in the far infra-red.

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Figure 3 - Over-all View of Mercury Lamp

The xenon arc lamp was mounted in a reflector which enabled about half the light output to be focused onto the converter windows. The xenon flash lamp was mounted in a diffuse reflector, and it is estimated that only one percent of the light output is incident on the converter window.

In the experiments, the lamps (except for the xenon arc lamp) were mounted as close as possible to the converter, usually approximately one-half inch. A rotating sector was placed between the lamp and the converter, thus permitting comparison of the converter characteristics with and without the radiation.

The calibration procedure for the CsI and the mercury lamps involved the use of a calibrated thermocouple and filters to select certain wavelength intervals. Since it was necessary to know the radiation flux at distances shorter than those for which the lamps could be calibrated, it was necessary to extrapolate the measured flux by assuming the

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inverse square law. Some calibrations were made using a tungsten filament and a grating spectrometer. If the temperature of the tungsten filament is known, then the energy per unit wavelength can be calculated and the intensity as read on the chart recorder can be calibrated. Thus, the energy in any particular line can be measured. These calibrations made on the CsI lamps agree fairly well with those made with the calibrated thermocouple and filters.

The 500-watt xenon arc lamp and the 200 watt-second xenon flash lamp were not calibrated because of the extreme nature of these lamps. The xenon arc lamp was focused into an intense spot while the time involved with the xenon flash lamp was of too short a duration (a milli-second). Estimates of the radiation intensity of these lamps were made from the published information on the spectral distribution for the two lamps. The effective absorption band for the first resonance lines of cesium was assumed to be $20\overset{\circ}{A}$ wide per line in this calculation.

As mentioned previously, film did form gradually on the sapphire window surface facing the emitter. Using the measurements of the temperature distribution across the emitter surface, the transmission can be calculated. These calculations yielded the estimates of the actual radiation entering the emitter-collector gap given in Table II. The transmission factor includes Fresnel reflection, absorption due to the film, and a factor of one-third to allow for the interception of the light by the tungsten wires. Note that these are very rough estimates of the radiation entering into the gap. This is especially true with regard to the two xenon lamps, where estimates were made of the geometric factors, and of the spectral intensity distribution. The geometric correction and absorption due to the film on the windows introduce large uncertainties which may be as high as 150 percent for the two xenon lamps.

EXPERIMENTAL PROCEDURE

Most of the testing was performed at cesium reservoir temperatures of $267^\circ C$ (0.6 Torr) and $325^\circ C$ (3.3 Torr). For all but the xenon flash lamp, the experimental procedure was to monitor the current-voltage curve with and without radiation for emitter temperatures from $1000^\circ K$ to $2150^\circ K$. For the xenon flash lamp, the experimental procedure was to monitor the short circuit current through a 0.001-ohm resistor. The change in current was measured on an oscilloscope during the flash.

Table II - Estimates of Radiation Incident on Converter Gap Due to
Various Radiation Sources

Lamp	Estimated Transmission of Windows and Film (percent)	Light Input into the Gap (watts/cm^2)
CsI-A	33	0.01 at 8943 and 8521 Angstroms
CsI-Hg	33	0.1 at 8943 and 8521 Angstroms
Hg lamp	46	0.03 at 2537 Angstroms
Xe arc lamp	23	0.07 in the ultra-violet 0.07 at 8943 and 8521 Angstroms
Xe flash lamp	16	0.8 at 8943 and 8521 Angstroms 1.0 in the near ultra-violet

The converters were originally designed such that, when cold, the minimum emitter-collector spacing was of the order of 0.002 inch. The actual spacing in the tantalum-emitter tube was as designed. In the tungsten-emitter converter, however, the spacing was such that the emitter would short to the collector after approximately one-half minute at the highest emitter temperature used (2200°K). (In the results reported, the spacing denoted as "close-space condition" represented that condition for which the bellows is relaxed and the spacing is determined by the rigid structural member.) Therefore, in the case of the tungsten emitter, the spacing was adjustable from approximately 0.001 inch at the highest emitting temperatures to about 0.080 inch. It is estimated that at the close-space condition, the spacing at low emitter temperatures could be as high as 0.007 inch. Most of the experimental measurements were taken for the two extreme spacing conditions.

The emitter temperatures are based on two calibrations made without cesium present, in which the brightness temperature as read by an optical pyrometer was measured as a function of the power input. The surface of the emitter contained two black-body holes for this purpose. The pyrometer readings were corrected for Fresnel reflection based on the assumption that the four surfaces of the two sapphire windows caused reflection. This gave an effective transmission of 73 percent for the

window combination. A correction for the heat conduction by cesium vapor was made based on the data of Kitrilakis and Meeker.[*] Note that no corrections were made for the electron cooling during the actual experiments when this calibration curve was used to obtain emitter temperatures from the power inputs. Electron cooling would tend to make the reported temperatures too high under conditions where large currents are flowing.

EXPERIMENTAL RESULTS

Some representative current-voltage curves for the tungsten-emitter converter are shown in Figure 4. These measurements are not optimized with respect to load, collector temperature, and cesium pressure. Figures 4a and 4b represent the usual converter operation, while Figure 4c represents the condition in which applied voltage is necessary in order to cause a discharge. Figures 4a and 4b yield efficiency of 4.5 percent and 3.8 percent respectively. This efficiency was obtained by dividing the anode output by the total electrical input. The converter output comes only from the tungsten disc at the end of the emitter cylinder - the area being defined by the guard ring.

All the lamps except the xenon flash lamp were similar in their effect on the converter. In general the results are as follows:

    a. Small increases in the pre-breakdown and discharge currents were observed at low emitter temperatures and large emitter-collector spacings.

    b. Some decrease in the required breakdown voltage has been observed. However, no change was observed in the maintenance voltage under any conditions.

    c. No significant change in current or voltage was observed when the tube was operated as a converter.

The increase in pre-breakdown current is reasonable, since any extra ions should have a large effect in overcoming space charge.[**]

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[*]S. Kitrilakis and M. Meeker. To be published in the proceedings of the Symposium on Thermionic Power Conversion, Colorado Springs, May 1962, Advanced Energy Conversion, Pergamon Press.

[**]F. L. Mohler, P. D. Foote, and R. L. Chenault, Phys. Rev., 27, 37 (1926).

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30 -				30 -			- 30
20 -				20 -			- 20
10 -				10 -			- 10

EMITTER TEMPERATURE = 2130°K
6.6 WATT/CM²

a.

EMITTER TEMPERATURE = 2002°K
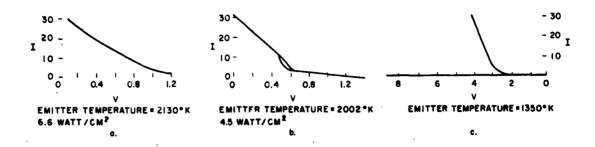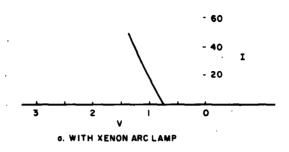4.5 WATT/CM²

b.

EMITTER TEMPERATURE = 1350°K

c.

Figure 4 - I-V Characteristic at Three Emitter Temperatures, a
Reservoir Temperature of 325°C, and With Close-
Spacing Condition

These increases can be as high as 50 percent in some cases, but the
over-all current is in the order of tens of milliamperes. The increase
in discharge current is usually in the order of 10 percent or less.

An example of the change in breakdown voltage is presented in
Figure 5. In general, there is little change in the breakdown voltage
for applied voltage just sufficient to cause a discharge. As the applied
voltage increases beyond this, the change produced by the radiation in
the breakdown voltage is larger. The fact that no change has been ob-
served in the minimum voltage necessary to maintain the discharge and
that no effect was observed in the converter mode of operation leads to
the conclusion that the radiation intensities necessary to perturb the
high-density plasma of the converter are greater than those available
from the first four radiation sources.

For the xenon flash lamp, whose radiation output is an order of
magnitude greater than the other sources, large effects have been ob-
served under all conditions of emitter temperatures and spacing, even
in the converter mode of operation (at least a 20-percent increase in
short-circuit current). These results, shown in Figure 6, present the
effect of the flash lamp on the short circuit current (R = 0.001 ohm) as
a function of emitter temperature for two spacings. Also shown are

- 60

- 40   I

- 20

3   2   1   0

V

a. WITH XENON ARC LAMP

- 60

- 40   I

- 20

4   3   2   1   0
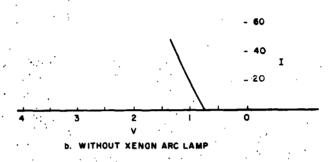
V

b. WITHOUT XENON ARC LAMP

Figure 5 - I-V Characteristic at an Emitter Temperature of
1210°K, a Reservoir Temperature of 325°C, and
With Close-Spacing Condition

the extrapolated Taylor-Langmuir electron emission curve for 325°C
reservoir temperature along with the calculated ion emission and 492 J_+
curves. Increases of at least one order of magnitude are observed in
the region on the lower temperature side of the 492 J_+ line where the
current is electron space-charge limited. Smaller increases due to the
radiation are observed in the ion rich case. In the electron rich case,
even with radiation, there is considerable electron space charge, since
the observed current with the lamp does not come up to the electron
emission curve. The effect of spacing is to reduce the current for all
temperatures with and without radiation, as would be expected in a dif-
fusion limited model. The dashed portion of the large spacing curve
without the radiation is caused by the change from the surface ionization
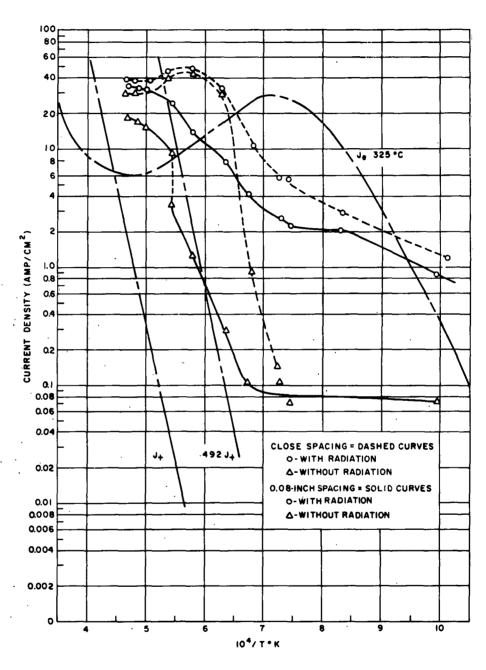mode to the volume ionization mode; this change was initiated by the flash.

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Figure 6 - Effect of Xenon Flash Lamp on Short-Circuit Current for
Two Spacings as a Function of Emitter Temperature, and
Cesium Reservoir Temperature of 325°C

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Why the curve for close spacing without the radiation is displaced considerably from the 492 J_+ line is not understood. An effect such as this could be caused by: (1) increased trapping of the positive ions, (2) the patch field effect being overcome at small spacing, and (3) a lower ionization potential species in the vapor such as Cs_2. The guard-ring current results are similar to the anode results for the large spacings, as expected, since the guard ring-to-emitter spacing is 0.065 inch. The magnitude of the currents with and without the radiation is slightly larger than the Taylor-Langmuir data in the ion rich region.

Using the appropriate band-pass filters, the effect of the various spectrum regions of the flash lamp can be determined. For example, at an emitter temperature of 1350°K, close-spacing condition, 33 percent of the increase in short circuit current is due to the first resonance lines. Approximately 14 percent of the effect is observed when a second order filter is used which will pass the second resonance lines. The first order band of this filter will also pass an undetermined smaller amount of the first resonance lines. Finally, 25 percent of the effect is observed when an ultra-violet band-pass filter is used. This accounts for 72 percent of the effect. The high order member of the principal series probably accounts for the remaining part of the effect. Combining these results with the light intensity calculation, it appears that one-third of the effect is caused by 0.8 watt/cm^2 of the cesium first resonance radiation, and that one-quarter of the effect is caused by 1 watt/cm^2 of radiation whose wavelength is shorter than that corresponding to the ionization potential of cesium. No significant change in output voltage was observed during these measurements, however, this is difficult to determine exactly.

The time dependence of the effect of radiation on the short circuit current of the converter was also observed and the results are presented in Table III.

Table III - 1/e of the Peak Value for Two Emitter Temperatures
Time (in millisecond) to reach 1/e of the peak value

	1960°K	1200°K
Light	0.66	0.73
Current	0.78	0.62

TIME SCALE • 0.2 µSEC/DIVISION

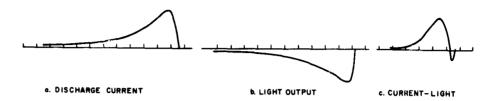a. DISCHARGE CURRENT   b. LIGHT OUTPUT   c. CURRENT-LIGHT

Figure 7 - Time Dependence of Light Induced Discharge
Current, Light Output, and the Time Difference
Between Both

In all cases it appears that the light precedes the current by 0.08 milli-second. This is shown in Figure 7 where data were taken at $325^{\circ}C$ reservoir temperature and the close-spacing conditions. Since the de-cay times are approximately equal, it appears that the loss processes for ions are faster than a fraction of a millisecond.

SUMMARY

The work during this quarter resulted in the completion of two ex-perimental converters designed specifically to keep the absorption path to a minimum. Five radiation sources were tested with the converters. The only radiation source that produced an effect on the converter oper-ation was the xenon flash lamp, because probably the radiation intensity of this lamp is an order of magnitude greater than the other sources used. Its effect in the ion rich region is to cause a 20-percent increase in the short-circuit current, while in the electron rich region at least one order of magnitude changes have been observed. However, in the latter region, the current is still space-charge limited.

M. D. Gibbons
June 3, 1963

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